MEMORANDUM

DATE: February 4, 2002

SUBJECT: Emissions Data for Reciprocating Internal Combustion Engines

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TO: Sims Roy, EPA OAQPS ESD Combustion Group

This memorandum presents a summary of hazardous air pollutants (HAP) and criteria emissions data gathered for stationary reciprocating internal combustion engines (RICE). The data presented in this memorandum were developed from 94 test reports for RICE, including tests conducted by EPA on three engines. These test reports are listed in Attachment 1. The test reports were gathered in an effort to characterize emissions from RICE from a variety of sources. The majority of these tests were performed for California AB2588 compliance purposes.

Source of Information

Alpha-Gamma developed a Microsoft Access database for the gathered data. The database includes the measured emissions concentrations and other parameters, such as temperature, flow rate, and horsepower, necessary to calculate emission rates and factors. The database also includes physical and operational parameters which may affect HAP and criteria emissions. Each record contains information for up to three test runs for an identified HAP or criteria pollutant. A database approach was chosen to easily access and manipulate the large amount of data collected. The database approach also ensures that all emissions are calculated consistently and reduces errors in the calculated emissions.

The majority of test reports included in the Emissions Database were obtained from California Air Resources Board (CARB) air basins and from the EPA STIRS (Source Test Information Retrieval System) effort. The database also includes emissions tests conducted by the Gas Research Institute (GRI) for natural gas-fired engines. These emissions tests were conducted by GRI in cooperation with GRI member companies. Testing was also conducted at Colorado State University (CSU) by EPA on three engines, and preliminary results of this testing are included in the Emissions Database.
The emissions tests obtained from state and local air regulatory agencies were conducted by source owners and operators in response to air regulatory requirements.
No standard protocol was used to conduct the emissions tests included in the RICE

Emissions Database. The pollutants, test methods, detection limits, operating conditions, and reasons for testing vary from test to test. The test reports gathered from California air pollution control districts were conducted by source owners and operators to comply with California's AB2588 air toxic regulations. In those cases, test methods developed and approved by the CARB are generally used to quantify emissions. The target HAP for the California tests vary since the target HAP were negotiated with the local air pollution control district.

Representation

The database contains a total of 578 tests. Of these tests, 431 were conducted on RICE that can be classified in one of the subcategories identified by EPA. A summary of the number of emissions tests included in the database, by subcategory, is presented in Table 1. The number of tests on engines with HAP control and small (<500 HP) engines is also given. Only seven test reports include simultaneous measurements of emissions before and after HAP control devices. Engines tested range in size from 25 horsepower (HP) to 7,107 HP. Most of the emissions data are for natural gas-fired engines and diesel engines, which, according to the RICE Population Database, represent over 95 percent of stationary RICE.

Table 1. Number of emissions tests per subcategory

Subcategory	Total Number of Emissions Tests	Number of Tests on Engines with HAP control	Number of Tests on Small Engines (< 500 HP)
2-Stroke Lean Burn (2SLB)	121	17	41
4-Stroke Lean Burn (4SLB)	94	16	0
4-Stroke Rich Burn (4SRB)	141	55	29
Compression Ignition (CI)	57	10	12
Digester Gas and Landfill Gas	18	0	6

For the fuels other than natural gas and diesel, there are a limited number of HAP emissions tests included in the RICE Emissions Database. For digester gas stationary RICE, 17 emissions tests are included in the database, and for landfill gas stationary RICE, one emissions test is included in the database. One emissions test is included in the database for propane and three emissions tests are included for process gas. No emissions tests are included for LPG engines. For CI stationary RICE, the majority of the

emissions tests included in the RICE Emissions Database are for diesel fuel; three tests are included for JP-5, and no emissions tests are included for dual fuel, kerosene/naphtha, or heavier fuels, such as residual/crude oil.

Emissions Data

HAP and criteria pollutant emissions data summaries are presented in Attachments 2 and 3, respectively. Emission concentrations are presented in units of parts per billion (ppb) for gaseous pollutants and micrograms per dry standard cubic meter (:g/dscm) for particulate pollutants. Emission rates are presented in units of pounds per hour (lb/hr) and emission factors are presented in units of pounds per million Btu heat input (lb/MMBtu) and pounds per horsepower-hour power output (lb/HP-hr). From the measured data, the following observations are made:

(1) formaldehyde, benzene, acetaldehyde, and acrolein are the most frequently tested HAP for natural gas fired engines;

(2) formaldehyde, naphthalene, and PAHs are the most frequently tested pollutants for diesel fired engines;

(3) the reported formaldehyde concentrations reflect the widest range of emissions for all fuel types;

(4) for landfill gas, all of the tested pollutants were detected;

(5) for digester gas, 1,1,1-trichloroethane, 1,3-butadiene, 1,4-dioxane, carbon tetrachloride, chloroform, ethylene dibromide, ethylene dichloride, tetrachloroethylene, trichloroethylene, and vinylidene chloride were never detected;

(6) for natural gas, 1,1,2-trichloroethane, 1,1-dichloroethane, 1,2-dichloroethane, 1,2-dichloropropane, 1-3-dichloropropene, carbon tetrachloride, chloroform, ethylene dibromide, and vinyl chloride were not detected; and

(7) naphthalene was not detected for propane fired engines.

Calculations

The emission factors and rates were determined using established EPA calculation methods. Emissions factors in lb/MMBtu were determined using calculation procedures presented in EPA Method 19, referenced in 40 CFR part 60, appendix A. These factors are based on the measured pollutant concentration, fuel factor, and stack oxygen levels. Emission rates in lb/hr were determined using standard engineering calculations and are

based on the measured pollutant concentration, exhaust stack flow rate, and the exhaust temperature. Emission factors in lb/HP-hr were based on the calculated emission rates (lb/hr), engine rating (HP), and load conditions. In cases where the fuel factor was not provided, EPA used the fuel factors provided in 40 CFR part 60.

Emission factors were calculated according to Equations 1 through 5 below. A detailed derivation of Equation 2 is provided in Attachment 4. For gaseous HAP, Equations 1 and 2 were used to calculate emission rates in lb/hr and emission factors in lb/MMBtu, respectively. For particulate HAP, Equations 3 and 4 were used to calculate emission rates in lb/hr and emission factors in lb/MMBtu, respectively. Equation 5 was used to calculate emission factors in lb/HP-hr for both gaseous and particulate HAP. Load conditions are incorporated into Equation 5 to account for engine output power.

Equation 1: Emission Rate in (lb/hr) for gaseous HAP:

$$ER\left(\frac{lb}{hr}\right) = \frac{1.369\times10^{-6}\left(\frac{lb\text{-}mol^{\circ}R}{ft^3}\right) \times 60\left(\frac{min}{hr}\right) \times Q_{stk}\left(\frac{dscf}{min}\right) \times C\,(ppb) \times MW\left(\frac{lb}{lb\text{-}mol}\right)}{(T_{ref} + 460)^{\circ}R}$$

where:

ER	=	Emission rate (lb/hr)
Q_{stk}	=	Stack gas flow rate (dscf/min)
C	=	Measured concentration (ppb)
MW	=	HAP molecular weight (lb/lb-mol)
T_{ref}	=	Standard temperature referenced (^{o}F)

Equation 2: Emission Factor in (lb/MMBtu) for gaseous HAP:

$$EF_F\left(\frac{lb}{MMBtu}\right) = \frac{1.369\times10^{-6}\left(\frac{lb\text{-}mol^{\circ}R}{ft^3}\right) \times F_d\left(\frac{dscf}{MMBtu}\right) \times C\,(ppb) \times MW\left(\frac{lb}{lb\text{-}mol}\right) \times \frac{20.9}{20.9 - \%O_2}}{(T_{ref} + 460)^{\circ}R}$$

where:

EF_F	=	Emission factor (lb/MMBtu)
F_d	=	Fuel factor (dscf/MMBtu)
$\%O_2$	=	Percent oxygen in the stack

Equation 3: Emission Rate in (lb/hr) for particulate HAP:

$$ER\left(\frac{lb}{hr}\right) = 3.70\times10^{-9} \times C\left(\frac{\mu g}{dscm}\right) \times Q_{std}\left(\frac{dscf}{min}\right)$$

where: C = Measured concentration (:g/dscm)

Equation 4: Emission Factor in (lb/MMBtu) for particulate HAP:

$$EF_F\left(\frac{lb}{MMBtu}\right) = 6.23\times10^{-11} \times C\left(\frac{\mu g}{dscm}\right) \times F_d\left(\frac{dscf}{MMBtu}\right) \times \frac{20.9}{20.9 - \%O_2}$$

where: C = Measured concentration (:g/dscm)

Equation 5: Emission Factor in (lb/HP-hr) for both gaseous and particulate HAP:

$$EF_p\,(lb/HP\text{-}hr) = \frac{ER\,(lb/hr)}{P\,(HP) \times \left(\frac{Load}{100}\right)}$$

where: EF_p = Emission factor based on power output (lb/HP-hr)
P = Power output (HP)
Load = Load conditions of the tested engine

Appendix: Detailed Information about Database

Presentation of Data

The accompanying database is presented in Microsoft Access Version 2.0 (ETD2_ICE.mdb) and in Microsoft Access 97 (ETDB9_01.mdb). It contains hazardous air pollutants (HAP) and criteria pollutant emissions data for internal combustion engines gathered from source test reports. A description of the various data fields in the database is included as Attachment 5.

As previously indicated, a total of 578 tests are included in the RICE Emissions Database. These tests were gathered from a total of 94 test reports, with 27 test reports containing information solely on HAP, 61 test reports containing information solely on criteria pollutants, and six test reports containing information on both criteria and HAP emissions. Some of the test reports represent pooled testing efforts of several engines or testing of the same engine under various loads. EPA assigned individual test ID numbers to each engine, for each load condition. For example, Report ID Number 11 contains three tests for three separate engines. In this case, the Test ID Numbers were assigned as 11.1 through 11.3. Each record corresponds to an individual test for a specific pollutant, and each test consists of three or less runs/measurements. In cases where less than three runs were conducted, an "NR" (not reported) indicates the run was not performed or was not valid.

The database contains two master tables, a “Facilities” table and a “Test Data” table. The common fields which link the two tables are the “Report” and the “ID” fields which contain the Source Report and Test Identification Numbers, respectively. A list identifying the gathered report numbers in the database is included with this document as Attachment 1. Three additional tables were created from the “Test Data” table: (1)Test Data - Criteria Pollutants, (2)Test Data - HAPs, and (3)Test Data - HAPs + Criteria. These tables subdivide the “Test Data” table by test reports which contain criteria pollutant emissions only, test reports which contain HAP emissions data, and test reports with both HAP and criteria pollutants. The data presented in the Facility and Test Data tables are “as reported” information. All calculations (corrected concentrations, emission rates, and emission factors) are performed within the database through the developed queries and modules. These calculations are automatically executed when selecting options presented in the Forms and Reports sections of the database.

Within the database, data were stored in two tables to reduce repetitive entry of data. These tables, and the data fields associated with each table are as follows:

Facilities Table

- Facility name
- Location
- Testing Company
- Date of Test
- Engine Manufacturer
- Engine Model
- Engine Family (2-stroke lean-burn, 4-stroke rich-burn, etc.)
- Air Supply (turbocharged, naturally aspirated, etc.)
- Number of Cylinders
- Rated Horsepower
- Test Horsepower
- Load
- Fuel Type
- Post-combustion Emission Controls

Test Data Table

- Pollutant
- Test Method
- Pollutant Concentration (as reported)
- Detection Limit
- Exhaust Oxygen Percentage
- Data Rating
- Fuel Exhaust Factor (F-Factor)
- Exhaust Flow Rate
- Fuel Heating Value
- Fuel Flow Rate
- Exhaust Moisture Fraction
- Molecular Weight of Pollutant

The database was programmed to merge data in the two tables and calculate emission factors for the available pollutants in units of pounds per horsepower-hour and pounds per million British thermal units of fuel burned. To ensure consistent calculation of emission factors, the database was programmed to use the emission concentration data and process data taken during the testing period to calculate the emission factors. Emission factors provided in each of the test reports were not used. This method of calculating emission factors was chosen because various methods of calculating emission factors were used in the gathered test reports. Also, in some cases, the method of calculating emission factors was not given.

Unreported emissions are presented as "NR." Unreported emissions are the result of missing parameters such as pollutant concentration, fuel type, engine type and size, stack exhaust flowrate, or fuel consumption levels. Typically, each test consisted of three test

runs. For the tests where at least one run (but not all runs) revealed an undetected concentration, a "<" sign precedes the calculated emission rates and factors. In cases where the pollutant was not detected in all test runs, the emission concentrations are presented as "ND". All emission rates and factors corresponding to undetected concentrations are calculated based on one half of the reported pollutant detection limit, and a "<<" sign precedes the calculated emission rates and factors. If the concentration is undetected and the pollutant detection limit is unknown, the emission rate or factor is shown as “NR” (not reported) with a “<<” sign. A detailed description of the calculation equations used to determine the emissions factors was previously presented in the memorandum.

The user can get a summary of emissions data by selecting the options under the “Forms” and the “Reports” sections of the database. The options presented in the Forms section allow the user to compile an emission factor for a specific pollutant for a selected engine type, size, load condition, and control application. The options presented in the Reports section provide the user with summaries of the gathered emissions data.

How to Use the Database

To use the database, open the database file which will automatically open the MAIN FORM view (in case where the MAIN FORM does not open, open the file and choose the FORMS selection on the main database screen, then under the FORMS selection, choose MAIN FORM).

To use the form section:

1- select the “Form” section by clicking on the form tab;
2- select and open the “Main Form” option;
3- select your search criteria, including the engine family, fuel type, engine size, test load condition, pollutant, control device, and the emission units of interest; and
4- once these factors have been identified, the user can either view the data that match the search criteria, or obtain the emission factors from the search criteria.

The following options are available to the user:

a- View Facilities

The VIEW FACILITIES function provides the user with specific information about the engine tested, test conditions, and pollution control devices. Each facility is a “record” as indicated at the bottom of the screen. To view the different facilities in the database, the user should click on the arrows at the bottom of the screen to progress through the various facility records. If the user wishes to search for a specific engine manufacturer, model, or family, the FIND option allows the user to

input a key word or number for the search. The value given in the ID field is a unique facility identification number which is used to cross reference between the FACILITY and TEST DATA databases. To exit this screen, click on the DONE button twice.

b- View EF Inputs

The VIEW EF INPUTS function provides the user with information used (or raw data) to generate emission factors for each test. This type of information includes horsepower, pollutant, F-factor, pollutant concentration, exhaust flow rate, moisture content of exhaust, and oxygen concentration in the exhaust.

c- EF Report

The EF REPORT option provides the user with the engines tested and the resulting emission factors for the selected search options.

The EF REPORT contains the column headings: database ID, engine manufacturer, engine model number, rated horsepower, operating load during testing, emission factors in the selected units, count (the number of runs in each test), and ND count (the number of runs where the pollutant was below the measurement detection limit).

At the end of each data series for a specific pollutant and engine family, summary statistics for the data set are provided. These include the following:

Average EF = The average of emission factors for a specific pollutant and engine family.

Std Dev = The standard deviation of the emission factors for the data set.

Count = The number of tests used to calculate an average emission factor.

RSD (%) = The relative standard deviation of the data set. This value is calculated by dividing the standard deviation by the average and multiplying by 100.

Summary of average concentrations and emission factors by fuel type and pollutant are presented in the “Report” section of the database. To use the “Report” section, select the report tab from the main screen. In order to obtain the calculated emissions data, you must open the desired report (when opening a report, you are basically running all related queries and modules).

NOTE: There are several options located in the TABLE, QUERY, FORM, REPORT, MACRO, and MODULE tabs that have not been addressed in this memorandum. These options are used to support the operation of the database and may not work or provide

useful information if chosen singularly. The user is advised to only exercise the options provided in the main screen.

Tests from the EPA's testing at CSU are identified by test identification numbers beginning with "CSU." Test identification numbers from 1 to 100 correspond to HAP. From 100 to 162, the identification numbers refer to tests with only criteria pollutants. Exceptions are report numbers 1, 29, 31 and the CSU test reports. Test number 1.1 contains only HAP, but tests number 1.2, 1.3, 1.4 and 1.5 contain only criteria pollutants. Reports 29 and 31 contain tests with both HAP and criteria pollutants and tests with only criteria pollutants (29.32, 29.40 and 29.43 and 31.10). As they all belong to the same facility, they were kept together with the same report identification numbers. The CSU test reports contain tests with both HAP and criteria pollutant data. Complete references of these test reports are included in Attachment 1.

Certain test report IDs include an "x" with the ID number. These reports are classified by EPA as suspect and the presented data may not reflect accurate emission measurements. In the case of reports 29 and 31, an x was added to indicate that the names of the facilities tested were not provided in the reports. Please note that the EPA is currently conducting certain QA/QC analysis procedures on the accompanying data. The data, as presented, have not been finalized.

Attachment 1
Source Test Identification Numbers

1. Osborne, W. E. and M. D. McDannel. Emissions of Air Toxic Species: Test Conducted Under AB2588 for the Western States Petroleum Association. Prepared by Carnot, Tustin, California for Western States Petroleum Association, Glendale, California. May, 1990.

2. Joint Powers Agencies for Pooled Emission Estimation Program. Final Report for Publicly Owned Treatment Works (POTWs). Appendix - Volume 1. Prepared by James M. Montgomery Consulting Engineers, Inc. for Publicly Owned Treatment Works, California. August, 1990.

3. Huey, S. and C. Castaldini. Effects of NOx Control on Pollutant Emissions in Natural-Gas-Fueled Stationary Engines. Topical Report (September 1991 - June 1992). Prepared by Acurex Environmental Corporation for Gas Research Institute. October, 1992.

4. Castaldini, C. and L. R. Waterland. Environmental Assessment of a Reciprocating Engine Retrofitted with Selective Catalytic Reduction. Project Summary. Prepared by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC. May, 1986.

5. Revised 1989 AB 2588 Emission Inventory Report. Marine Corps Air Ground Combat Center, Twentynine Palms, California. Volume III. AB 2588 Source Test Report. Prepared by Science Applications International Corporation, Environmental Services Division, San Diego, California, for Southwest Division, Naval Facilities Engineering Command, San Diego, California, June, 1993.

6. Source Emissions Survey of Los Angeles International Airport - Diesel Fired Generating Units, Los Angeles, California. Prepared by Metco Environmental, Dallas, Texas, for ERM-West, Inc. October, 1990.

7. Pooled Source Emission Test Report: Gas-Fired IC Engines in Santa Barbara County. Prepared by ENSR Consulting and Engineering, Camarillo, California, for ARCO Oil and Gas Company, Bakersfield, California. July, 1990.

8. AB 2588 Diesel Emission Test Summary. Prepared by Thermochem, Inc., Laboratory and Consulting Services, Santa Rosa, California, at The Geysers, for Six Participating Geothermal Operator Companies. November, 1990.

9. Porter, T. Ventura Port District Dredge : Air Toxics Emissions Retesting, Ventura Harbor, Ventura, California. Prepared by BTC Environmental, Inc., Ventura, California for Applied Environmental Technologies. February 25, 1991.

10. Air Pollution Source Testing for California AB 2588 on an Oil Platform Operated by Chevron USA, Inc., Platform Hope, California. Prepared by Engineering-Science, Pasadena, California for Chevron USA Inc., Ventura, CA. August 29, 1990.

11. Air Pollution Source Testing for California AB 2588 of Engines at the Chevron USA, Inc. Carpinteria Facility. Prepared by Engineering-Science, Pasadena, California, for Chevron USA, Inc., Ventura, California. August, 1990.

12. Source Emissions Survey of Vandenberg Air Force Base, Engines No. 1, 2, 3 and 4 Exhaust Stacks, Vandenberg, CA, Volume 1. Prepared by Metco Environmental, Dallas, Texas for Versar, Inc. May and June, 1990.

13. Compliance Report of Hydraulic Dredge "Ollie" Application # 1266-111. Prepared by South Coast Environmental Company, La Verne, California, for Reidel International, Portland, Oregon. Parameters Measured: Formaldehyde, Poly Aromatic Hydrocarbons (PAH's)and Multiple Metals by Fuel Analysis. March 8, 1991.

14. Air Emission Testing of Internal Combustion Engines for Chevron USA Production Company, Carpinteria, CA, Tested by Engineering Science, Inc. March, 1992.

15. Western States Petroleum Association, Bakersfield, California. Pooled Source Emission Test Report: Oil and Gas Production Combustion Sources, Fresno and Ventura Counties, California (Without Appendices). Prepared by: ENSR Consulting and Engineering. January, 1991.

16. Finnie, S. and T. Wong. Source Emissions Testing Final Test Report. Volume 1. Pooled Source Testing of a Rig Diesel-Fired Internal Combustion Engine. Prepared by Entropy Environmentalists, Inc., Huntington Beach, California for Western States Petroleum Association, Bakersfield, California. October 2, 1992.

17. Source Testing of a Diesel-Fired Generator Engine at the U.S. Naval Communications Facility in Stockton, California. Prepared by BTC Environmental Inc., Ventura, CA. 1990.

18. Air Pollution Source Testing for California AB 2588 at the Naval Weapons Center, China Lake, CA. Prepared by Engineering-Science, Inc., Irwindale, CA, for Kern County Air Pollution Control District, Bakersfield, CA. November 4, 1991.

19. AB 2588 Air Toxics Emission Testing at PRCC - IC Engine. Prepared by Steiner Environmental, Inc., Bakersfield, California, for Rand Mining Company, Randsburg, California. December, 1991.

20. Air Toxics Hot Spots Testing at Southern California Gas Company, Goleta Station - IC Engine # 3. Prepared for: Southern California Gas Company Test Center. Prepared by: Pape & Steiner Environmental Services. June, 1990.

21. Texaco Exploration & Production Inc. Gas Compressor Emissions Testing. Final Report. Prepared for Texaco Exploration & Production Inc., Ferndale, Washington, by Emission Technologies, Inc., Burlington, Washington. June 26, 1995.

23. AB 2588 Air Toxics Emission Testing at PRCC - IC Engine. Prepared for Products Research and Chemical Corporation, Mojave, California, by Steiner Environmental, Bakersfield, California. December, 1991.

24. Espinosa, V. Emissions from an Internal Combustion Engine Fueled by Landfill Gas. Source Test Report Conducted at GSF Energy, Inc., Olinda Landfill Power Station, Internal Combustion Engine, Brea, California, by South Coast Air Quality Management District, El Monte, California. July 15, 1988.

25. AB2588 Source Testing at the Naval Petroleum Reserve # 1 for the Department of Energy and Chevron, at Elk Hills, CA, Engines K-27 (report ID 25.1), K-36 (ID 25.2), K-49 (ID 25.3), K-70 (ID 25.4). Prepared by : Petro Chem Environmental Services, Inc. Prepared for : Chevron USA, Inc., Bakersfield, CA. February, 1992.

26. Engineering Test Report at Asilomar Conference Center, Pacific Grove, California. Prepared by South Coast Environmental Company, Orange, California. December 31, 1991.

27. Source Test Emission Report for the Delaval Engine at the Central Heating Facility and the Waukesha Engine at the Athletic Facility of UC Santa Cruz, California. Prepared for Santa Cruz Cogeneration Associates, Fairfield, California by Best Environmental, Inc., San Leandro California. September 22, 1992.

28. Shih, C.C., et al. Emissions Assessment of Conventional Stationary Combustion Systems; Volume II Internal Combustion Sources. Prepared by TRW, Inc., Redondo Beach, California for US EPA, Office of Research and Development, Washington, DC (Contract No. 68-02-2197). EPA-600/7-79-029c. February, 1979.

29. GRI Topical Report, Measurement of Air Toxic Emissions from Natural Gas-Fired Internal Combustion Engines at Natural Gas Transmission and Storage Facilities, Volume II: Appendices. Prepared by: Gas Research Institute. February, 1996.

30. Air Toxic “Hot Spots” Emissions Inventory Report, Dregde “Headway”, Ventura Harbor, California. Prepared for: Dutra Dredging Company, Job No. 0060-01. Prepared by: Applied Environmental Technologies, Inc. May 31, 1990.

31. GRI Topical Report, Measurement of Air Toxic Emissions From Combustion Equipment at Natural Gas Processing Plants, Volume II: Appendices. Prepared by: Gas Research Institute. November 1997.

101. Compliance Emission Test Report, Phillips Petroleum Company, Lake Washington Central Battery No. 1 Generator. Prepared by: Environmental Science & Engineering, Inc. October, 1992.

102. Compliance Source Test At The Naval Petroleum Reserve #1 For The Department Of Energy and Chevron, At Elk Hills, CA, Engines K-70 (report ID 102.1 and 102.2) and K-71 (report ID 102.3 and 102.4). Prepared By: Petro Chem Environmental Services, Inc. Prepared For: Chevron USA, Inc., Bakersfield, CA. May 25 and July 22, 1993 (ID 102.1, 102.2) and May 11, 1992 (ID 102.3, 102.4).

103. Test for UNOCAL, Santa Monica, CA, Tested by Petro Chem Environ Services. October, 1988.

104. Source Test Report, Oxides Of Nitrogen And Carbon Monoxide, Emission Test Results For Internal Combustion Engines At Garden City Compressor Station. ESE No.: 3907022000. Prepared By: HUNTER/ESE, Inc., Baton Rouge, LA. Prepared For: Louisiana Intrastate Gas Corporation, Alexandria, LA. September 1989.

105. Emission Testing on Compressor Engines #3 and #4 at Avery Island FWD and Compressor Station No. 1, New Iberia, Louisiana, Tested by Emission Testing Services, Inc., Baton Rouge, Louisiana. December, 1992.

106. Oxides Of Nitrogen And Carbon Monoxide, 5A Compressor. Report No.: 87037. Prepared By: Emission Testing Services, Inc., Baton Rouge, LA. Prepared For: Arco Oil And Gas Company, St. Mary Parish, LA. October 6, 1987.

107. Compliance Test Report for Battles Gas Plant, UNOCAL Corporation, Orcutt, CA. Prepared by: Petro Chem Environmental Services. November, 1992.

108. I.C. Engine Emission Tests at Southern California Gas Goleta Station. Report PS-90-2255. Prepared by Pape & Steiner Environmental for Southern California Gas Company. September, 1990.

109. Emission Testing On TPLI Unit #2 At The Lake Barre Booster Station. File No.: 92024. Prepared By: Emission Testing Services, Inc., Baton Rouge, LA. Prepared For Texaco Pipeline, Inc., Houston, TX. March 19, 1992.

110. W. Schneider, Air Pollution Control Engineer, Division Of Technical Services And Monitoring, Bureau Of Air Quality Control, Commonwealth of Pennsylvania to Peoples Natural Gas Company, Laurel Ridge Compressor Station, Jackson Township, Cambria County, PA. Memorandum: Source Test Review For Non-methane Hydrocarbons, Nitrogen Oxides, And Carbon Monoxide. April 14, 1992.

111. Source Tests Reports for Bechtel Petroleum Operations, Inc., Elk Hills Naval Petroleum Reserve, Tupman CA, tested by Petro Chem Environmental Services, Inc., April 1991.

112. Internal Combustion Engines - Source Test Emissions Summary Report #086-211. Unocal, Orcutt, California. November, 1992.

113. Compliance Source Test At The Naval Petroleum Reserve #1 For The Department Of Energy and Chevron, At Elk Hills, CA, Engine K-43. Prepared By: Petro Chem Environmental Services, Inc. Prepared For: Chevron USA, Inc., Bakersfield, CA. April 16, 1991.

114. T. Bianca, Air Pollution Control Engineer, Division Of Technical Services And Monitoring, Bureau Of Air Quality Control, Commonwealth of Pennsylvania to National Fuel Gas Supply Corporation, Alleghany Township, Potter County, PA. Memorandum: Source Tests To Determine Carbon Monoxide, Nitrogen Oxides, And Total Non-methane Hydrocarbons. January 30,1991.

115. T. Bianca, Air Pollution Control Engineer, Division Of Technical Services And Monitoring, Bureau Of Air Quality Control, Commonwealth of Pennsylvania to National Fuel Gas Supply Corporation, Alleghany Township, Potter County, PA. Memorandum: Source Tests To Determine Carbon Monoxide, Nitrogen Oxides, And Total Non-methane Hydrocarbons. January 30, 1991.

116. Annual Compliance Test, Chevron USA, Warren Gas Plant, Internal Combustion Engine #'s 1 & 2. Report No.: 7777-0301. Prepared By: Genesis Environmental Services Company, Bakersfield, CA. Prepared For: Chevron USA, Inc., Bakersfield, CA. October 1, 1991.

117. Oxides Of Nitrogen And Carbon Monoxide Emission Testing On K-402 Compressor. Report No.: 90028. Prepared By: Emission Testing Services, Inc., Baton Rouge, LA. Prepared For: Mobil Oil Corporation, Chalmette, LA. March 28-29, 1990.

118. Compliance Emission Test Report, Phillips Petroleum Company, Lake Washington Central Battery, No. 4 Compressor. Prepared By: Environmental Science and Engineering, Inc.. Prepared For: Phillips Petroleum Company. January, 1993.

119. IC Engine Emission Tests on three Points within the City of Tulare's Sewage Treatment Plant, Tested by Steiner Environmental, Inc. April, 1993.

120. Annual Compliance Test, Coalinga Station, Pipeline Plant, Engines #1. Report No.: 291-101, Job No.: 21999. Prepared By: BTC Environmental, Inc., Ventura, CA. Prepared Unocal, San Luis Obispo, CA. June 26, 1991.

121. Unocal Corporation, Coalinga Lease, Coalinga, California. Prepared by: Petro-Chem Environmental Services, Inc. (PCES). May 14, 1993.

122. Emission Testing On The Hammock Station Compressor, Longwood Grace Unit, (Section 5). File No.: 92082b. Prepared By: Emission Testing Services, Inc., Baton Rouge, LA. Prepared For: Gulf States Pipeline Corporation, Shreveport, LA. July 29, 1992.

123. Oxides Of Nitrogen And Carbon Monoxide Emission Testing, Engine 83-01 and 84-01, Wilcox Production Facility CF #3, Lockhart Crossing Field. Prepared By: Emission Testing Services, Inc., Baton Rouge, LA. Prepared For: Amoco Production Company, Lafayette,LA. September 7-8 and October 30, 1989.

124. Source Test Report, Hunter Resources, Santa Barbara, CA, Kobe Well Pump Engine, Tested by SCEC, Orange County, CA. March, 1992.

125. M. Hopko, Air Quality Program Specialist, Division Of Technical Services And Monitoring, Bureau Of Air Quality Control, Commonwealth Of Pennsylvania, to Texas Eastern Gas Pipeline Company, Holbrook Compressor Station, Richhill Township, Greene County, PA. Memorandum: Sampling and Analysis of 17 Engines and 1 Combustion Turbine at the Holbrook Compressor Station, for CO_2 and O_2 concentrations, NOx CO, O_2 and Unburned Hydrocarbon Concentrations for Turbines. January 23-29, 1991.

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Attachment 2
Summary of HAP Emissions Data for
Internal Combustion Engines

Attachment 3
Summary of Criteria Emissions Data for Internal Combustion Engines

Attachment 4
Detailed Derivation of Equation 2

Emission Factor in (lb/MMBtu) for gaseous HAP is given in 40 CFR part 60, appendix A, Method 19, Eqn. 19.1 as:

$$EF_F \left(\frac{lb}{MMBtu}\right) = C_d \left(\frac{lb}{dscf}\right) \times F_d \left(\frac{dscf}{MMBtu}\right) \times \frac{20.9}{20.9 - \%\ O_2}$$

for gaseous pollutants:

(Eqn. 1)

$$C_d \left(\frac{lb}{dscf}\right) = C \left(\frac{lb\text{-}mol_{HAP}}{lb\text{-}mol_{air}}\right) \times MW \left(\frac{lb_{HAP}}{lb\text{-}mol_{HAP}}\right) \times \frac{1}{V_{molar}} \left(\frac{lb\text{-}mol_{HAP}}{dscf}\right)$$

where:
- C is the measured concentration
- MW is the Molecular Weight
- V_{molar} is the molar volume
- F_d is the fuel factor as provided in the test report (F_d and V_{molar} have to be at the same standard temperature)
- O_2 is the exhaust stack oxygen level

The concentration can be expressed as:

$$C \left(\frac{lb\text{-}mol_{HAP}}{lb\text{-}mol_{air}}\right) = C \left(\frac{ppb}{10^9}\right)$$

and assuming ideal gas:

$$PV = nRT$$

(Eqn. 2)

$$V_{molar} = \left(\frac{V}{n}\right) = \left(\frac{R\,T}{P}\right) = 0.73 \left(\frac{dscf\ atm}{lb\text{-}mol\ ^\circ R}\right) \times \frac{T\ (^\circ R)}{P\ (atm)}$$

Also, $T\ (^oR) = T\ (^oF) + 460$

@ 68 ^oF and 1 atm, V_{molar} from Eqn. 2 becomes:

$$V_{molar} = 0.73 \times (68 + 460) / 1 = 385.5 \text{ dscf/lb-mol}$$

and Eqn. 1 becomes:

$$C_d \left(\frac{lb}{dscf}\right) = C(ppb) \times 10^{-6} \times MW \left(\frac{lb_{HAP}}{lb\text{-}mol_{HAP}}\right) \times \frac{1}{385.5} \left(\frac{lb\text{-}mol_{HAP}}{dscf}\right)$$

Eqn 19.1 becomes:

$$EF_F\left(\frac{lb}{MMBtu}\right) = \frac{C(ppb) \times 10^{-6} \times F_d\left(\frac{dscf}{MMBtu}\right) \times MW\left(\frac{lb}{lb\text{-}mol}\right)}{385.5\ \left(\frac{dscf}{lb\text{-}mol_{air}}\right)} \times \frac{20.9}{20.9 - \%\ O_2}$$

However, not all testing companies use standard conditions of T = 68^{o}F (some use 60^{o}F) and presents the fuel factor based on a different standard temperature; therefore, for these reports, the molar volume has to be adjusted to compensate for this variation. Here is where the temperature correction comes in place.

Assuming that the fuel factor is provided at a temperature of T_{ref}, then Equation 2 becomes:

(Eqn.3)

$$V_{molar} = 385.8 \times (T_{ref} / T_{std@68\ ^oF})$$

$$V_{molar} = 385.5 \times (T_{ref\ in\ ^oF} + 460) / (460 + 68)$$

$$V_{molar} = 385.5 \times (T_{ref\ in\ ^oF} + 460) / 528 \text{ , therefore}$$

Substituting Eqn. 3 in Eqn. 1

$$C_d\left(\frac{lb}{dscf}\right) = C(ppb) \times 10^{-9} \times MW\left(\frac{lb_{HAP}}{lb\text{-}mol_{HAP}}\right) \times \frac{1}{\frac{385.5}{528}(T_{ref}+460)}\left(\frac{lb\text{-}mol_{HAP}}{dscf}\right)$$

which can be re-written as:

$$C_d\left(\frac{lb}{dscf}\right) = C(ppb) \times 10^{-9} \times MW\left(\frac{lb_{HAP}}{lb\text{-}mol_{HAP}}\right) \times \frac{528}{385.5\ (T_{ref}+460)}\left(\frac{lb\text{-}mol_{HAP}}{dscf}\right)$$

Note that 528 / (T_{ref} $^{o}_{F}$ + 460) is the temperature correction factor to 68^{o}F, therefore, Eqn. 1 becomes:

$$C_d\left(\frac{lb}{dscf}\right) = C(ppb) \times 10^{-9} \times MW\left(\frac{lb_{HAP}}{lb\text{-}mol_{HAP}}\right) \times \frac{1}{385.5}\left(\frac{lb\text{-}mol_{HAP}}{dscf}\right) \times (Temperature\ Correction)$$

Substituting in Eqn 19-1 of 40 CFR 60, App. A, Method 19, the emission factor equation in lb/MMBtu becomes:

$$EF_F\left(\frac{lb}{MMBtu}\right) = \frac{C(ppb)\times 10^{-9}\times F_d\left(\frac{dscf}{MMBtu}\right)\times MW\left(\frac{lb}{lb\text{-}mol}\right)}{385.5\left(\frac{dscf}{lb\text{-}mol}\right)} \times temperature\ correction \times oxygen\ correction$$

Note, the oxygen correction factor is equal to 20.9 / (20.9 - %O_2) and the temperature correction is equal to 528 / (T_{ref} + 460). Substituting in these values, the emission factor equation in lb/MMBtu becomes:

$$EF_F\left(\frac{lb}{MMBtu}\right) = \frac{1.369\times 10^{-9}\left(\frac{lb\text{-}mol^{\circ}R}{ft^3}\right) \times F_d\left(\frac{dscf}{MMBtu}\right) \times C\ (ppb) \times MW\left(\frac{lb}{lb\text{-}mol}\right) \times \frac{20.9}{20.9\ -\ \%\ O_2}}{(T_{ref}\ +\ 460)^{\circ}R}$$

This is the equation presented in the Background Document of Section 3.1 of the AP-42.

Attachment 5

Definitions of Database Fields

The Facilities table contains the following fields:

Report	-	The Report Identification Number. This is an indexed field. Each report may contain one or more tests depending on the number of units tested, test rating, controlled versus non controlled emissions and so on. Tests are indicated by the ID field.
ID	-	The Test Identification Number. The ID corresponds to the test reference number within a report.
Facility Name	-	The name of the facility.
Location	-	The location of the test site.
Testing Company	-	The name of the company that conducted the test.
Date	-	The date the test was performed.
Manufacturer	-	The name of the engine manufacturer.
Model	-	The engine model designation.
Engine Family	-	Describes the type of engine and the air/fuel ratio.
Charging Type	-	The type of charging the engine utilizes.
Cylinders	-	The number of combustion cylinders.
Rating	-	The rating of the engine
Unit	-	The rating units.
Test Rating	-	The rate at which the test was conducted.
TRUnit	-	The test rating units.
Load	-	The load at which the engine is operated during the test.
Fuel Type	-	The fuel used for charging.
Control Device	-	The type of device used to control emissions.
Application	-	What is the engine used for.
Comments	-	Any comments, supplemental information and underlying assumptions.
Data Quality	-	Observations about the validity of the data.
Data Entered By	-	Person that entered the data.

The two tables are related through the Report and ID fields.

The Test Data table consists of the following fields:

Report	-	The Report Identification Number.
ID	-	Test Identification Number.
Pollutant	-	The name of the pollutant.
Method	-	The method used for sampling and quantification of pollutant.
Run 1 Conc R	-	The reported concentration for Run 1.
Run 2 Conc R	-	The reported concentration for Run 2.
Run 3 Conc R	-	The reported concentration for Run 3.
DL	-	The detection limit reported for the pollutant.

SD - The number of significant digits.
Avg Conc R - The average of the reported concentration for all runs.
Cunit - The units used for reported concentration.
Run 1 O_2 - The percent oxygen in the exhaust measured in Run 1.
Run 2 O_2 - The percent oxygen in the exhaust measured in Run 2.
Run 3 O_2 - The percent oxygen in the exhaust measured in Run 3.
Run 1 Rate - The reported pollutant emission rate for Run 1.
Run 2 Rate - The pollutant emission rate reported for Run 2.
Run 3 Rate - The pollutant emission rate reported for Run 3.
Avg Rate - The average pollutant emission rate for all runs.
R Unit - The units for the pollutant emission rate.
Run 1 Factor - The pollutant emission factor reported for Run 1.
Run 2 Factor - The pollutant emission factor reported for Run 2.
Run 3 Factor - The pollutant emission factor reported for Run 3.
Fac Unit - The units for the pollutant emission factor.
Fuel Factor - The F-factor for the fuel used for firing (dscf/MMBtu).
Run 1 Gas Flow rate - The exhaust gas flow rate for Run 1.
Run 2 Gas Flow rate - The exhaust gas flow rate for Run 2.
Run 3 Gas Flow rate - The exhaust gas flow rate for Run 3.
Gas Flow rate Units - The units for the exhaust gas Flow rate.
Fuel Heating Value - The heating value of the fuel.
Fuel HV Units - The units for the fuel heating value.
Standard Temp. - The standard temperature used for the emission calculations.
Standard Temp. Units - The units for the standard temperature.
Stack Temp. - The reported stack temperature.
Stack Temp. Units - The reported stack temperature units.
Run 1 Fuel Flow rate - The fuel firing rate in Run 1.
Run 2 Fuel Flow rate - The fuel firing rate in Run 2.
Run 3 Fuel Flow rate - The fuel firing rate in Run 3.
Fuel Flow rate Units - The units for the fuel firing rate.
Run 1 % Moisture - The amount of moisture detected in the exhaust for Run 1.
Run 2 % Moisture - The amount of moisture detected in the exhaust for Run 2.
Run 3 % Moisture - The amount of moisture detected in the exhaust for Run 3.
MW - The pollutant molecular weight.
Comments - Any comments, supplemental information and underlying assumptions.